MpCCI: Neutral Interfaces for Multiphysics Simulations

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1 Introduction

In various research and engineering fields, there is a growing demand for more realistic simulations covering all relevant aspects from different simulation disciplines—the multiphysical or multidisciplinary simulations. Fluid-structure interaction (FSI), magneto-hydro dynamics, thermal radiation or manufacturing process chains define only a subset of multiphysics applications.

To this purpose, Fraunhofer SCAI has developed flexible vendor neutral interfaces since 1996 in order to transfer simulation data from one tool to another—either at run-time or file-based. The tools provide methods and algorithms to translate (i.e. map) the data to the software-specific syntax and to the problem-specific discretization. The mapping algorithms use the finite element or finite volume formulation (i.e. the shape functions) of the source mesh in order to interpolate the data onto the target mesh, cf. the MpCCI documentation [4].

The main software product MpCCI CouplingEnvironment provides a framework for co-simulations: the data is repeatedly exchanged at run-time in a bi-directional way. This allows to combine specialized simulation tools in order to create a commonly converged multiphysical result. The tool is applied for multiphysical phenomena which require a high degree of interactions.

For application examples, where the influence of the fluid dynamics or the electromagnetics to the thermal or mechanical behavior of a structure is higher than vice versa, it is sufficient to map the load conditions once. To this purpose the file-based software MpCCI FSIMapper has been developed.

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Simulation of complex manufacturing processes to predict structural product characteristics does often require a serialized chain of distinct simulation disciplines. To achieve realistic simulation results, local material properties have to be mapped as initial conditions to each step of the virtual process chain [6]. The MpCCI Mapper provides a vendor neutral interface for such simulation workflows. Typical application areas are passive safety for automotive vehicles, optimization of forming tools, and design of composites manufacturing process and products.

The following sections describe the MpCCI concepts and selected multidisciplinary applications. Parts of these product and application descriptions are excerpts from other sources [2, 5–8, 10, 11, 14].

2 MpCCI CouplingEnvironment

MpCCI CouplingEnvironment has been developed for the simulation of multiphysical phenomena. For simulation disciplines like finite element analysis (FEA), computational fluid dynamics (CFD), multibody systems (MBS), electromagnetics (EM), etc., a lot of specialized commercial or open-source simulation tools are available on the market. However, in many cases the combination of different simulation disciplines cannot be realized within a closed software environment from a single vendor [10].

On this account, an application independent interface for the direct coupling of different simulation codes has been designed: MpCCI CouplingEnvironment. It has been accepted as a 'de facto' neutral standard for simulation code coupling. Its multiphysics framework provides a complete and ready-to-use co-simulation environment with a dedicated user front end and visualizer system.

To ensure best interoperability between the codes, MpCCI CouplingEnvironment has established a standardization of coupling procedures independent from the utilized codes and coupling quantities definition. The supported simulation codes are shown in Fig. 1.

MpCCI CouplingEnvironment provides a coupling manager which automatically organizes the communication of the coupled codes [10]. The software employs a staggered approach for all co-simulation problems which can be defined as

- a globally *explicit* coupling method: the coupled fields are exchanged only once per coupling step. This approach is applicable to problems with weak physics coupling.
- an *implicit* iterative coupling method: the coupled fields are exchanged several times per coupling step until an overall stabilized solution is achieved before advancing to the next coupling step. This approach is applicable to problems with strong physics coupling.

Complementary to the coupling method, MpCCI CouplingEnvironment offers two coupling algorithms—Gauss-Seidel and Jacobi (Fig. 2):

- The *Gauss-Seidel* coupling scheme is also known as serial or "Ping-Pong" algorithm where one code waits while the partner code proceeds.

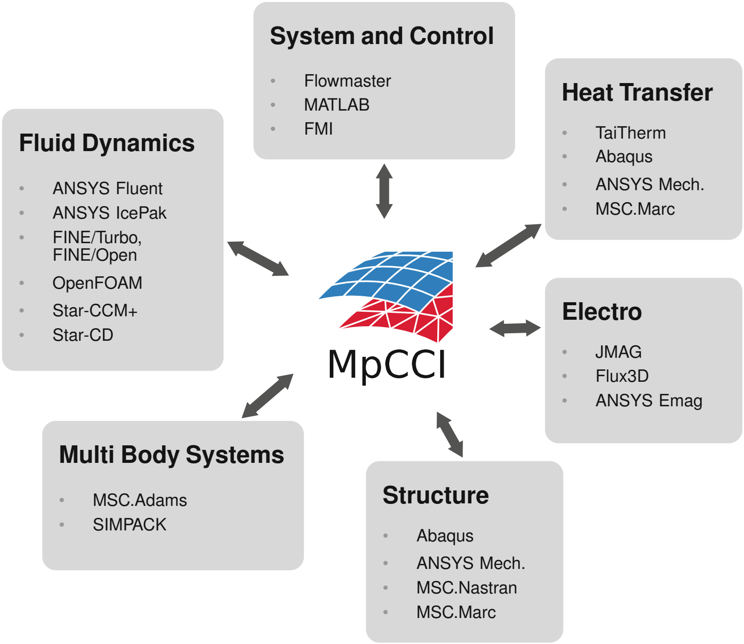

Fig. 1 MpCCI CouplingEnvironment's list of supported simulation codes (December 2016). Published with kind permission of ©Fraunhofer SCAI 2016. All Rights Reserved

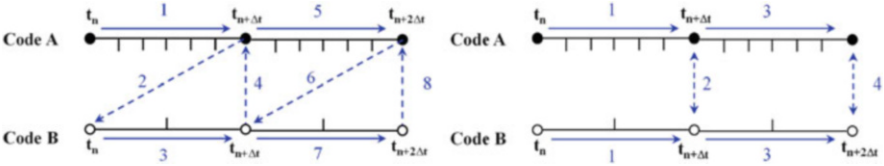

Fig. 2 Flow diagram for the Gauss-Seidel coupling scheme (*left*) and the Jacobi coupling scheme (*right*). $t_{n+\Delta t}$ represents the physical time t at time step $n + \Delta t$. Δt is the coupling time step size [10]. Published with kind permission of ©Fraunhofer SCAI 2016. All Rights Reserved

- The *Jacobi* coupling scheme is also known as a parallel algorithm where both analysis codes run concurrently.

MpCCI CouplingEnvironment will automatically exchange the data between the meshes of two or more simulation codes by using interpolation methods and considering the nature of the quantities exchanged. The co-simulation application can exchange nearly any kind of data between the coupled codes; e.g. energy and momentum sources, material properties, boundary condition values, mesh definitions, or global quantities.

To provide a stabilization of the coupling iteration, relaxation algorithms (fixed factor, ramping or automatic) are implemented. For problems with different time scales or adaptive time stepping, MpCCI CouplingEnvironment offers a time-interpolation.

In the following, various multiphysical problems solved with MpCCI Coupling-Environment are presented.

2.1 Aero-Elasticity and Fluid-Structure-Interaction

One of the most common examples of multiphysics simulations is a fluid-structure interaction (FSI) simulation: when a surrounding fluid exerts pressure on a flexible structure, this structure deforms which leads to changes in the flow field of the fluid. The fluid mesh has to adapt to the new position computed by the structure simulation code [8].

This effect can be observed in different application areas, for example when studying the aerodynamic performance of aircraft wings or spoilers of racing cars or while investigating machine dynamics of valves, pumps or hydraulic engine mounts.

Although FSI simulations have been in use for a long time already, depending on the fluid and solid properties, the choice of the right coupling algorithm and the mesh motion on the CFD side might be challenging.

The two following selected applications highlight different aspects of FSI with deformable structures.

2.1.1 Wing and Spoiler Design

Aircraft wings and racing car spoilers are surrounded by fast moving air, as shown in Fig. 3. The pressure building up on the surface of the wings and spoilers leads to deformation of the solid parts. To predict the behaviour of the wing during flight a coupled FSI simulation is necessary [15].

The deformation of the wing or spoiler elements is calculated with an FEA simulation software, e.g. Abaqus or MSC.Nastran. This FEA code is then coupled—via MpCCI CouplingEnvironment—with a CFD code (Fluent, Star-CCM+ or OpenFOAM) calculating the fluid flow. Depending on the investigated driving or

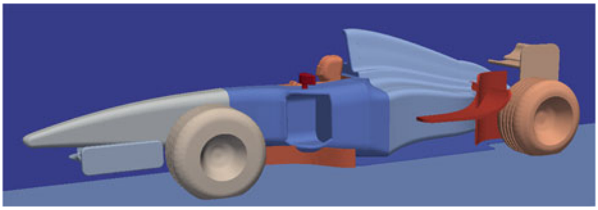

Fig. 3 CFD model of racing car. Rear wings are investigated using FSI simulations [8]. Published with kind permission of ©Fraunhofer SCAI 2016. All Rights Reserved

flight conditions, different coupling algorithms can be used: either steady state or transient simulations can be coupled. Only with a coupled simulation, the behaviour of wings (e.g. flutter) or the performance of a racing car spoiler using drag and lift coefficients can be predicted.

2.1.2 Hydraulic Pump Layout

With the help of numerical simulation a new high-pressure hydraulic axial pump has been developed at Gdansk University [19], see Fig. 4. To find an optimal layout of the different pump chambers, coupled FSI simulations using Abaqus, Fluent and MpCCI CouplingEnvironment were used.

The pump is equipped with a compensation chamber with an elastic membrane. During phases with high pressure, this membrane deforms, giving the fluid more room and thereby reducing harmful pressure peaks.

The CFD model consists of all pump chambers—including the compensation chamber—and implements the movements of the pistons. The hydraulic oil is assumed to be slightly compressible to achieve a stable coupling. Abaqus/Explicit is used to compute the deformation of the elastic wall of the compensation chamber. Very small time steps are necessary for the coupled simulation.

While a CFD stand-alone simulation is not capable of reproducing the experimental measurements for the pump, the coupled simulation results show a very good agreement with the experiments and thus have been used to optimize the geometric layout of the compensation chamber and the materials for the elastic wall.

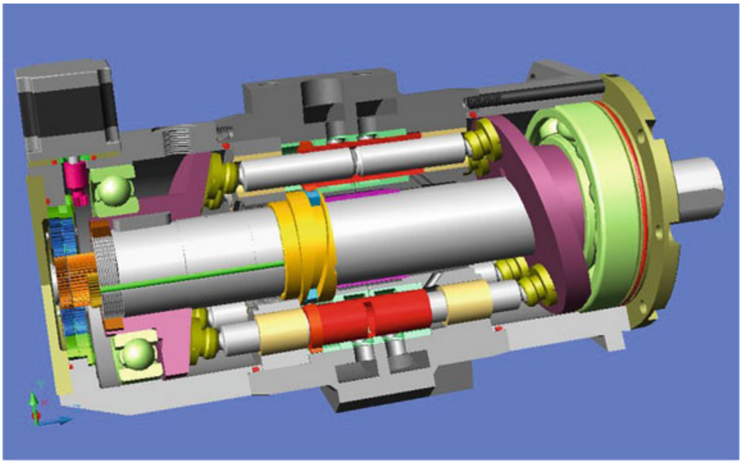

Fig. 4 Constant displacement PWK pump with four chambers [16]. Published with kind permission of ©Fraunhofer SCAI 2016. All Rights Reserved

2.2 Thermal and Vibration Loads in Turbomachinery

The development of highly efficient turbo-machines makes the detailed knowledge of the mechanical, thermal and fluid dynamic processes indispensable. They serve for optimization of the flow geometry, thermal stresses, lifetime, etc. Realistic simulation of a turbomachinery system often requires the knowledge of boundary conditions, which usually are the results of other simulation disciplines or are even strongly interrelated with each other [11].

The following selected applications highlight different solution strategies for turbomachinery design.

2.2.1 Thermal Loads on Ceramic Impeller

In order to increase the efficiency of micro gas turbines by increasing the gas temperatures, it is necessary to consider new material concepts for the high temperature loaded parts. The solution strategy targets to compute a realistic temperature distribution in turbo-machines. For the analysis of the heat transfer, well chosen thermal boundary conditions are necessary. This includes, among other things, the heat input to the structure resulting from the flow field (cf. Fig. 5). The heat flux to solid parts is influenced by the difference between the fluid and the structural wall temperature. The wall temperature is in turn dependent on the effective heat flux. Only if both entities are at equilibrium, the actual component temperatures are reached. Fraunhofer SCAI used a thermally coupled FINE/Turbo—Abaqus solution to create a new ceramic impeller design [24].

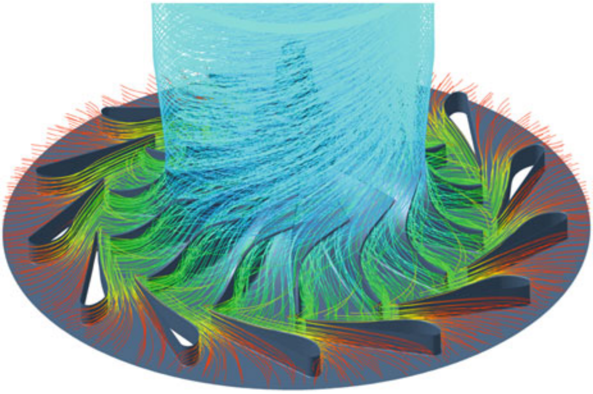

Fig. 5 Turbomachinery flow paths colored by the temperature [11]. Published with kind permission of ©Fraunhofer SCAI 2016. All Rights Reserved

2.2.2 Life-Time Estimation of Turbine Blades

Flow-induced vibrations can lead to a high noise emission and to blade fatigue which can endanger the integrity of the whole system. Excitations are caused by pressure fluctuations in the flow field generated mainly by interactions between rotating and stationary blade rows. To estimate the long term behavior and high-cycle fatigue in operation, it is necessary to know the periodic pressure oscillations of the flow and thus the excited oscillations of the turbine blades. A transient coupling of the fluid pressure and the blade deformation delivers stress oscillations and thus gives the basis of fatigue analyses [11].

2.3 Vehicle Dynamics and Nonlinear Component Behavior

Analysis of multibody systems (MBS), finite element analysis (FEA), and computational fluid dynamics (CFD) are well established practices in computational engineering. The simulation of multibody systems is mainly used for the analysis of mechanisms consisting of rigid components connected with joints to represent the whole system dynamics. The FEA and CFD methods allow much more detailed investigations of the system behavior. They need, however, more computational resources and are time consuming compared to the MBS simulation. The following selected examples highlight some applications where co-simulation with MBS codes provides an accurate result and is a good strategy compared to standard computational engineering methods [2, 14].

2.3.1 Driving Over Obstacles

For some critical situations, e.g. driving over an obstacle (Fig. 6), the misuse of components over the vehicle dynamics needs to be investigated. Various automotive original equipment manufacturers (OEMs) use a combination of Abaqus and MSC. Adams to model the nonlinear behavior of single critical components, e.g. transverse links, and their interaction with the complete vehicle system model. All critical components are modeled with Abaqus in order to calculate the nonlinear response from the multibody system in MSC.Adams which provides the kinematic constraints of the whole system. This solution strategy has provided a considerable reduction of the total amount of simulation time compared to a full FEA analysis. Especially analysis types with a strong dependency on accuracy, like e.g. fatigue life calculations, can benefit from co-simulation [2].

2.3.2 Wading Simulation for Off-Road Vehicles

Vehicle wading refers to a situation where a vehicle traverses through water at different speeds, cf. Fig. 7. One of the major challenges is computing the inertial

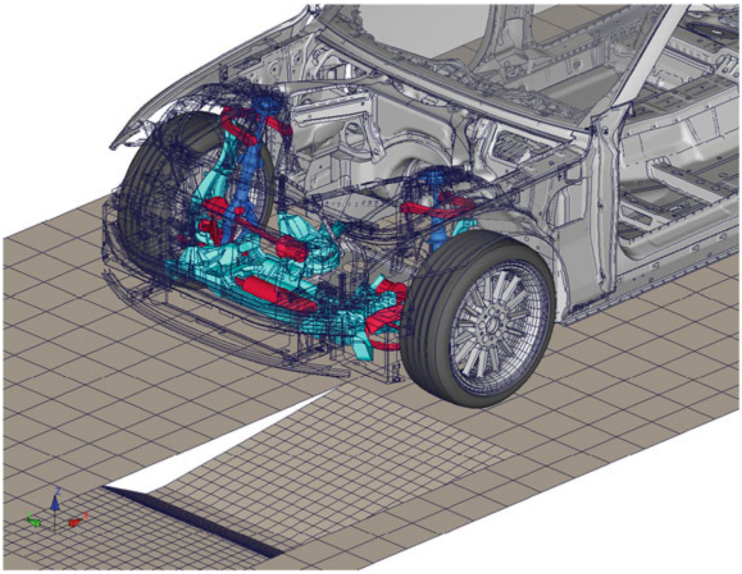

Fig. 6 Coupled FEA-MBS model of a car driving over an obstacle [2]. Published with kind permission of ©Fraunhofer SCAI 2016. All Rights Reserved

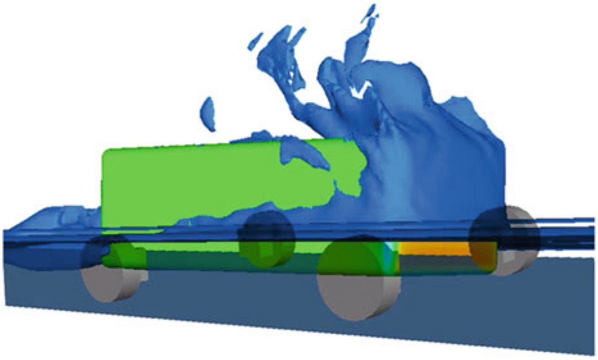

Fig. 7 Wading of a car through deep water modelled by a simplified block in STAR-CCM+ [14]. Published with kind permission of ©Fraunhofer SCAI 2016. All Rights Reserved

field of a vehicle while wading. In cooperation with an automotive OEM, Fraunhofer SCAI has developed a new method of co-simulation between CFD (STAR-CCM+) and MBS (SIMPACK) [14]. This solution strategy provides a new level of design and analysis capabilities to the industrial users.

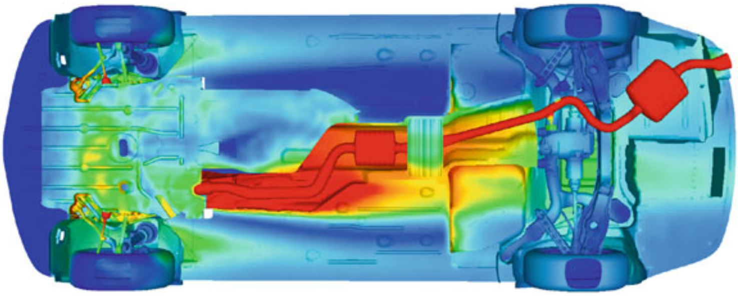

Fig. 8 Temperature distribution on the underbody of a full vehicle [1]. Published with kind permission of ©Fraunhofer SCAI 2016. All Rights Reserved

2.4 Automotive Thermal Management

The calculation of underhood component temperatures of entire passenger cars requires the consideration of different heat transport phenomena: convection, conduction and radiation. In addition to conjugate heat transfer models, the application of separate software tools dedicated to certain transport mechanisms is still demanded by users due to applicability, computing time or other company specific reasons. For these coupled approaches, a co-simulation environment like MpCCI is yet needed. The following applications highlight different aspects of thermal management for automotive engineering (Fig. 8).

2.4.1 Automotive Thermal Management for Full Vehicles

Calculation of the thermal behavior of automotive vehicles requires simulations for the full complexity of a vehicle's geometry and transport phenomena of heat including convection, radiation and conduction in fluids and solid bodies [5]. With regard to an accurate prediction of the temperature distribution of the entire car, radiation plays an important role in the overall heat management calculation. In areas with a relevant temperature influence (e.g. engine compartment, gear box or exhaust system), convective heat transfer and radiation are calculated in a coupled environment. As transient problems like dynamic drive cycles gained lately more importance in the development stage, the implementation of fast but accurate quasi-transient simulation approaches is further advanced [1]. For these specific tasks, OEMs frequently use a combination of TAITherm with STAR-CCM+ or in-house CFD solvers.

2.4.2 Automotive Thermal Management for Vehicle Manifolds

An important issue in automotive industry is to provide temperature distributions for vehicle components as input for following stress analyses. The transfer of temperature fields, heat transfer coefficients and film temperatures in an engine exhaust manifold may illustrate the importance of the thermal coupling in the transient heating due to the flow of the internal hot exhaust gas stream. The temperature distribution may be used to calculate the temperature expansion and resulting stresses as accomplished in [17].

2.5 Component Design in Electrical Engineering

The prediction of heating and cooling processes is of eminent importance in the development of electrical devices. The alternating current induces heating due to losses by Ohm's law, and the usual mechanism for cooling is free convection. The increasing tendency of miniaturization requires to fully exploit the thermal potential of the materials involved. The following two selected applications highlight different aspects of electrical component design [7].

2.5.1 Cooling of a 3-Phase Transformer

The thermal performance of an oil-immersed power transformer is governed by the oil flow for the transfer of heat generated in the windings and core towards the tank and the surrounding air. A coupled JMAG-Fluent model has been used to detect the local hot spots [22] within the device. The Joule losses calculated by JMAG are used as source terms for Fluent which conducts a thermal analysis taking into account the transport phenomena of heat including convection and conduction in fluids (coolant and air) and solid bodies (core and coils). The resulting temperature distribution for the core and coils will affect the electrical property of the copper material, which is temperature dependent, and will induce a new distribution of Joule losses. The temperature distribution in coils is very important because heat resistant designs are required for safety.

2.5.2 Electric Arc in Switching Devices

Switching arcs, as shown in Fig. 9, can be modeled using ANSYS EMAG to solve the magnetic field problem and Fluent to solve the fluid dynamics problem—coupled in volume through MpCCI CouplingEnvironment [21]. Based on magneto-hydrodynamic equations, a 3D model for a switching arc considering Lorentz forces, ohmic heating and radiation transport can be developed using a co-simulation approach. Beside the co-simulation solution, which allows to subdivide a complex problem in smaller problems, the challenge still remains in modeling the plasma. The modeling of the electric arc behavior is governed by different stages, e.g. the arc motion, the arc elongation, the arc commutation and arc cutting process. The inclusion of all these phenomena in the analysis requires to consider

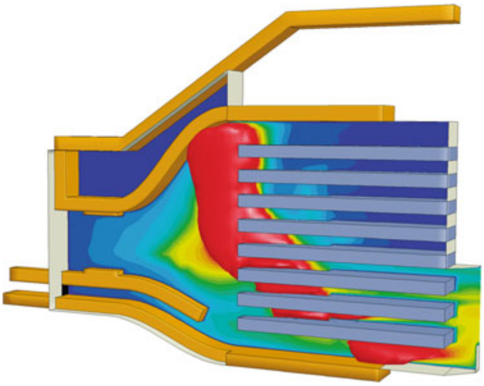

Fig. 9 Plasma temperature of an electric arc in a switching device [7]. Published with kind permission of ©Fraunhofer SCAI 2016. All Rights Reserved

additional models like the arc root, the material erosion, etc. The resulting physical and material model of the electric arc provides methods and references for the optimization work of switching devices.

3 MpCCI FSIMapper

For many problems the influence of the CFD on the FEA solution is more significant than vice versa, e.g. when structural deformation caused by thermal expansion or pressure loading does not affect the flow field. Thus, a one-way transfer of the stationary fluid solution to the solid solver as boundary condition is a time-saving and good approximation to a co-simulation. Therefore, Fraunhofer SCAI has designed a file-based tool to address application cases where a single one-way transfer is sufficient.

MpCCI FSIMapper allows to read data of various CFD result formats as well as an EM result format (see Fig. 10). The universal EnSight Gold format can be exported by diverse CFD tools which enlarges the practicability.

Thermal and mechanical loads can be transferred to an FEA model to be used in a subsequent structural analysis. The tool exports a file including the mapped boundary conditions using the syntax of Abaqus, ANSYS Mechanical, or Nastran.

The quantities that can be transferred are volume temperature, film temperature, wall heat transfer coefficient, wall heat flux, pressure and forces. The two meshes, between which the interpolation of physical entities shall take place, have to be either surface meshes or volume meshes. Robust and efficient interpolation schemes allow the data transfer for different discretization accuracy or even in non-matching model regions using extrapolation.

The mapping of static, transient (only MagNet .vtk, EnSight Gold .case) and harmonic (only FINE/Turbo .cgns, EnSight Gold .case) results is offered. A Fourier transformation of transient force or pressure data is provided in order to create the loading for NVH (noise vibration harshness) analyses.

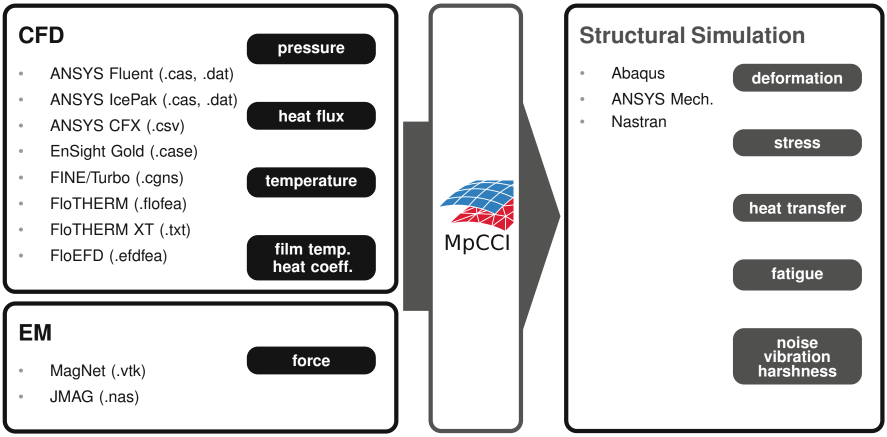

Fig. 10 Schematic view of the capabilities of MpCCI FSIMapper. In the *left*, the importable file formats are listed, in the *right* the available solver formats for exporting the mapping result (December 2016). Published with kind permission of ©Fraunhofer SCAI 2016. All Rights Reserved

If the models, between which the mapping shall take place, are defined in different unit systems or if their position and orientation differ from each other, MpCCI FSIMapper provides on the one hand an automatic and on the other hand a user defined transformation (translation and rotation) in order to generate geometrically coinciding models. Also, the mapping between periodic models which differ only with respect to their section shape is possible.

In the context of frozen-rotor analyses, the simple mapping of the thermal or mechanical loading would lead to an unbalanced structural behavior. In order to produce a blade-wise average, MpCCI FSIMapper offers the possibility to build an "average over rotation", where the mean is built over sections defined by a certain pitch angle.

Furthermore, with MpCCI FSIMapper it is possible to compare the geometric shape of used models to locate and evaluate differences in modeling the particular domain.

The tool has a graphical user interface but can also be used in batch.

4 MpCCI Mapper Solution for Integrated Simulation Workflows

Simulation of complex manufacturing processes to predict structural product characteristics does often require a chain of distinct simulation disciplines. Each simulation step typically requires a specific problem discretization to handle the physical effects. To achieve realistic simulation results, local material properties have to be specified as initial condition at each step of the virtual process chain.

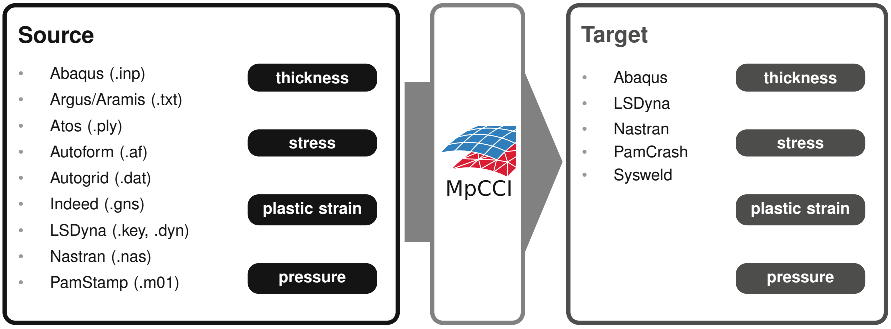

Fig. 11 MpCCI Mapper list of file interfaces supported (December 2016). Published with kind permission of ©Fraunhofer SCAI 2016. All Rights Reserved

In addition to the transfer of local material properties along a manufacturing chain, simulation models have to be validated by comparison with experimental test results [9].

In order to transfer local material properties between consecutive simulation steps, Fraunhofer SCAI has developed MpCCI Mapper to supply a link between the different computer-aided engineering (CAE) tools involved in the process chain.

For instance, the mechanical properties, like material thinning or plastic strain from a sheet metal forming process, can be integrated in the structural design process of crash relevant automotive body components.

MpCCI Mapper provides advanced and robust methods to map, compare and transfer simulation results and experimental data in integrated simulation workflows. It supports a growing number of native file formats (Fig. 11) and can be used in a variety of engineering applications.

The MpCCI Mapper software is a standard tool in the engineering departments of most German automotive OEMs and has been validated in the VDA/FAT working group *Formed Chassis Parts* for Forming to Crash workflows.

In the subsequent sections, some application areas are presented, where the manufacturing history is significant for the component behavior.

4.1 Passive Safety

For the accurate prediction of the structural behavior of metal sheet car body components, the local manufacturing history must be taken into account. Local reduction of material thickness, stresses, plastic strain and other material properties, e.g. the local crystalline structure of high-strength steel resulting from single manufacturing steps such as deep drawing, immersion lacquering, and welding, may have significant influence on the resulting car body component. As local material properties may vary during a manufacturing process, result information has to be transferred downwards the process chain. In [12, 18, 23] it was shown that only the

Fig. 12 Car seat crash simulation [18]. Published with kind permission of ©Fraunhofer SCAI 2016. All Rights Reserved

consideration of the manufacturing history of high strength steels leads to a good correlation of simulation and experimental testing. Figure 12 shows the application in the crash simulation of a seat system.

4.2 Forming Tools and Material Properties

4.2.1 Lightweight Stamping Tools: Use Forming Loads in Structural Optimization

The combination of increased diversity of automotive parts and the pressure for decreased tool development times results in the need for optimization of the structural layout of stamping tools. A number of German OEMs have used MpCCI Mapper to transfer the maximal pressure loads from the stamping process into a structural optimization environment. The optimization process thus can consider local stamping loads to determine improved designs with less total mass but the same stability [20].

4.2.2 Validation of Material Model Parameters: Compare Forming Results and Experimental Data

Due to the stringent requirements with respect to feasibility, stability and crash performance, exact models for the specific material behavior are required. This validation process is supported by the comparison of different simulation or experimental results with each other. MpCCI Mapper has been used to obtain information about the deviation of results either in a section or over the whole geometry of a component [3].

4.3 Composite Structures and Plastic Components

4.3.1 CFRP Workflows: From Draping via Mulling and Curing to Structural Analysis

The excellent mass-specific properties of carbon-fiber reinforced plastics (CFRP) can be tailored to the actual requirements and make CFRP well qualified for use in lightweight constructions. However, the economical exploitation of these theoretical potentials is currently limited by insufficiencies of manufacturing processes, by lack of knowledge of the material behavior and by insufficient prediction of the structural performance. These weaknesses can only be solved by establishing a close collaboration between the three disciplines of methods, materials and processes. Another important precondition for improving CFRP applications is an integrated simulation of the entire CFRP process chain, where all significant process parameters and process results are transferred between the single simulation steps.

In a research project, KIT Karlsruhe has used the MpCCI Mapper technology to link the process steps from draping via molding and curing to the final structural analysis of a prototype trunk lid geometry, see Fig. 13 [13].

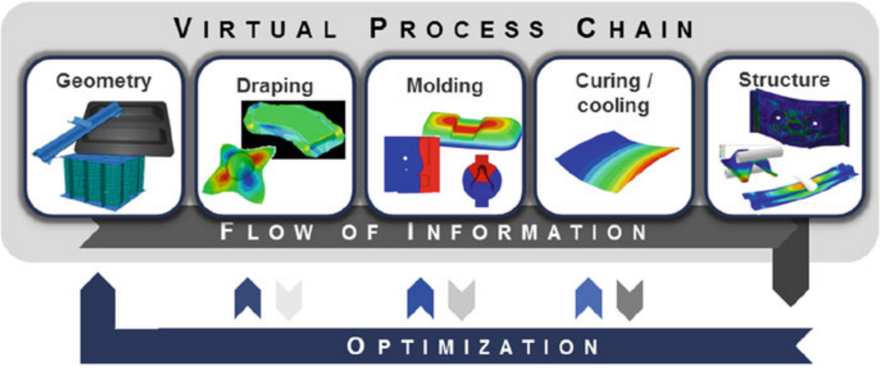

Fig. 13 Virtual process chain combining design, process and structural simulation for a CFRP workflow [13]. Published with kind permission of ©Fraunhofer SCAI 2016. All Rights Reserved

4.3.2 Structural Integrity of Blow Moulded Plastic Components

Within a research project, MpCCI Mapper was used to transfer local material properties and orientations from the BSim simulation as initial conditions for a subsequent structural analysis. This simulation workflow is essential for a range of standard products: from plastic bottles to complex automotive components like fuel tanks.

5 Conclusion

Coupled multiphysics simulation and simulation workflows consisting of different simulation steps can help to implement more realistic models. For each of the relevant physical effects, most suited simulations tools can be applied and combined in a larger application scenario. The benefits of the interface solution MpCCI are its neutrality and openess to all commercial software vendors. MpCCI Coupling-Environment provides a flexible way to run co-simulations of two or more codes at once; the MpCCI Mapper solutions give a simpler path for a 1-way data transfer.

While the MpCCI interface solutions are already used in many different application domains and industrial sectors, there are still open issues which need to be solved during the next years: The combination of full 3D models (fluid dynamics, structural analysis) with complex system models (e.g. a complete 1D vehicle model) or the seamless transfer of local material properties in a multi-disciplinary simulation workflow still require more sophisticated synchronisation algorithms and standardised export and import facilities for the different simulation tools in a CAE chain.

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